APPLICATION OF THERMO-MECHANICAL MEASUREMENTS OF PLASTIC PACKAGES FOR RELIABILITY EVALUATION OF PEMS

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Abstract

Thermo-mechanical analysis (TMA) is typically employed for measurements of the glass transition temperature (Tg) and coefficients of thermal expansion (CTE) in molding compounds used in plastic encapsulated microcircuits (PEMs). Application of TMA measurements directly to PEMs allows anomalies to be revealed in deformation of packages with temperature, and thus indicates possible reliability concerns related to thermo-mechanical integrity and stability of the devices.

In this work, temperature dependencies of package deformation were measured in several types of PEMs that failed environmental stress testing including temperature cycling, highly accelerated stress testing (HAST) in humid environments, and burn-in (BI) testing. Comparison of thermo-mechanical characteristics of packages and molding compounds in the failed parts allowed for explanation of the observed failures. The results indicate that TMA of plastic packages might be used for quality evaluation of PEMs intended for high-reliability applications.

Introduction

Excessive mechanical stresses in dice and fracture of wire bonds due to deformation of plastic packages, which are caused by mismatch of CTE between the molding compound (MC) and the lead frame (LF), are considered as one of the major failure mechanisms specific to plastic encapsulated microcircuits. To reduce mechanical stresses in the dice, a buffering layer of silicone die coating (usually drop-on coating) is used in many linear devices sensitive to mechanical stresses. Extensive investigations of the effectiveness of the silicone die coating have shown that in some cases they might adversely affect reliability of the parts [1, 2]. In particular, it has been shown that relatively thick silicone coatings might increase the probability of failures during temperature cycling [3]. This requires a thorough analysis and a method to evaluate risks associated with usage of die coatings in PEMs.

Another possible mechanism of failure is due to excessive deformations of plastic packages as a result of swelling of the MC in humid environments [4]. Moisture sorption in plastic packages degrades mechanical characteristics of MCs, resulting in decrease of the glass transition temperature and reduction of adhesion between the MC and LF. This, together with expansion of the MC due to moisture-induced swelling, might result in delaminations between the LF and MC during HAST, thus providing a path for moisture and corrosive contaminations to penetrate to the die surface. Excessive delaminations were often observed on plastic devices failing HAST; however, this effect has not been properly analyzed and explained.

Application of TMA for measurements of thermo-mechanical characteristics of MC directly on PEMs has been analyzed in [5]. It has been shown that anomalies in deformations of plastic packages might be due to the presence of the LF, sorption and desorption of moisture, and the presence of internal mechanical stresses, which result in warpage of packages. Elimination of these errors allows for accurate measurements of Tg and CTE to characterize molding compounds used in PEMs.

In this work, anomalies in the TMA characteristics of plastic packages are used to reveal excessive deformations, which resulted in formation of rejectable defects and/or failures in the parts. Three case histories are described in which employment of TMA has helped in understanding the mechanism of failures during reliability testing of PEMs.

Experiment

In this study, the temperature dependence of the deformation of plastic packages and epoxy molding compounds was measured using a thermal mechanical analyzer, TMA2940, manufactured by TA Instruments. To avoid warpage-related errors, the characteristics of molding compounds were measured on small pieces of the devices cut from the packages. Experiments have shown that the best reproducibility is achieved when testing is performed at a rate of 3 °C/min. during cooling from 220 °C, followed by heating of the sample in the analyzer at the same rate. This allows for monitoring of the stress-relief effect in samples and assures elimination of possible errors related to the presence of moisture and built-in mechanical stresses. Measurements of package deformations were carried out directly on plastic parts with a probe centered above the die on the surface of the package.

Case History I: HAST-Induced Delaminations

Multiple failures due to delaminations were observed after HAST at 130 °C/85% RH for 96 hours in comparator microcircuits encapsulated in plastic SOT-23-5 packages. The parts had normal electrical characteristics; however, delaminations, which were observed mostly at the lead finger-tips (see Figure 1), were considered critical due to the wire bond integrity concerns.

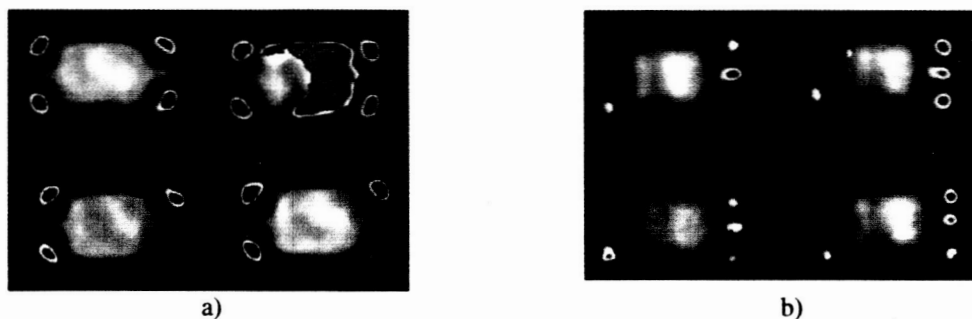a)   b)

Fig. 1. Example of delaminations at the finger-tips on the top (a) and the bottom (b) of the SOT-23-5 packages after HAST.

To evaluate the risk related to the observed defects, three groups of the devices were tested: 15 parts after HAST, 15 parts from the same lot date code (DC0018) that failed C-mode scanning acoustic microscopy (C-SAM) examinations during screening, and 5 parts from another lot (DC 0020) that were used for comparison purposes. It was assumed that due to close date codes, these lots had similar characteristics. Three samples of each group were characterized for Tg and package deformations using a thermo-mechanical analyzer. Results of these measurements are shown in Figure 2 and Table 1.

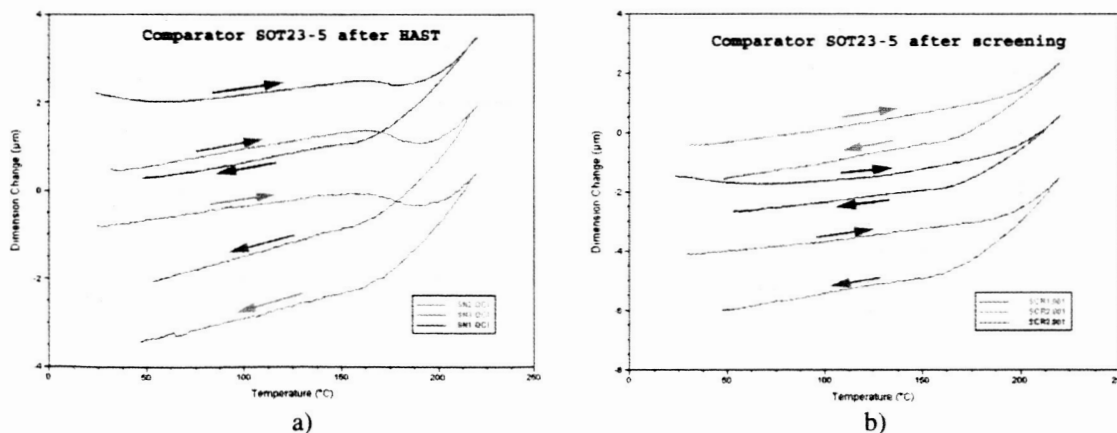a)   b)

Fig. 2. Temperature dependence of package deformations for three samples: a) after HAST, b) after screening.

Note that all samples after HAST had a significant hysteresis, with the increasing branch of the TMA curves being much higher than the decreasing one. The value of this hysteresis was evaluated by a relative deformation (dL/L) calculated at 50 °C. Results of these calculations are also shown in Table 1.

Lot	Tg, °C	CTE1, ppm/°C	CTE2, ppm/°C	dL/L, %
After HAST, DC 0018	170.1 (1.1)	9.2 (1.7)	37.3 (3.7)	0.21 (0.04)
After Screen, DC 0018	171.1 (0.3)	9.1 (1.8)	42.6 (7.2)	0.12 (0.05)
Initial, DC 0020	164.3 (0.7)	10.25 (0.8)	65.5 (4.0)	

Tab. 1. Glass transition temperatures (Tg), coefficients of thermal expansions (CTE), and hysteresis (dL/L) of the three groups of the comparators. Average values and standard deviations are shown in parentheses.

The results show that samples with DC 0018 after HAST and after screening had similar Tg and CTE values; however, the hysteresis was much larger for the HAST parts, indicating swelling of the molding compound. This swelling is most likely the major reason of excessive delaminations observed after HAST.

The TMA testing was performed in ~1,000 hours after HAST. With the thickness of parts, h = 1.15 mm, the characteristic time of moisture diffusion, which also indicates the time necessary to dry out the package, can be estimated as $\tau = h^2/4D$, where D is the diffusion coefficient. Calculations yield $\tau \approx 520$ hours at room temperature. This means that most of the moisture absorbed during HAST should have been released from the package by the time of TMA measurements. The observed excessive hysteresis suggests that the exposure to high-temperature/high-humidity conditions during HAST has resulted in irreversible deformations of the molding compound and formation of delaminations.

It is interesting to note that microcircuits with DC 0020 and DC 0018 had different molding compounds, thus suggesting that commercial parts with even close date codes might be manufactured using different materials, and that the TMA measurements are capable of discriminating among different encapsulating materials.

Delaminations after HAST testing were observed on parts that passed screening. This indicates that similar defects potentially can develop with time due to moisture-induced swelling and creep in molding compound, even in samples that initially had no delaminations.

To evaluate the risk related to the presence of delaminations in these devices, all samples in the three groups were subjected to preconditioning according to JEDEC standard JESD22-A113 (three runs through the solder reflow chamber) and temperature cycling from -55 °C to 125 °C. The parts were tested after 100, 300, and 1,000 cycles. No failures were observed during this testing, and the parts manifested only minor changes in their electrical characteristics, as shown in Figure 3.

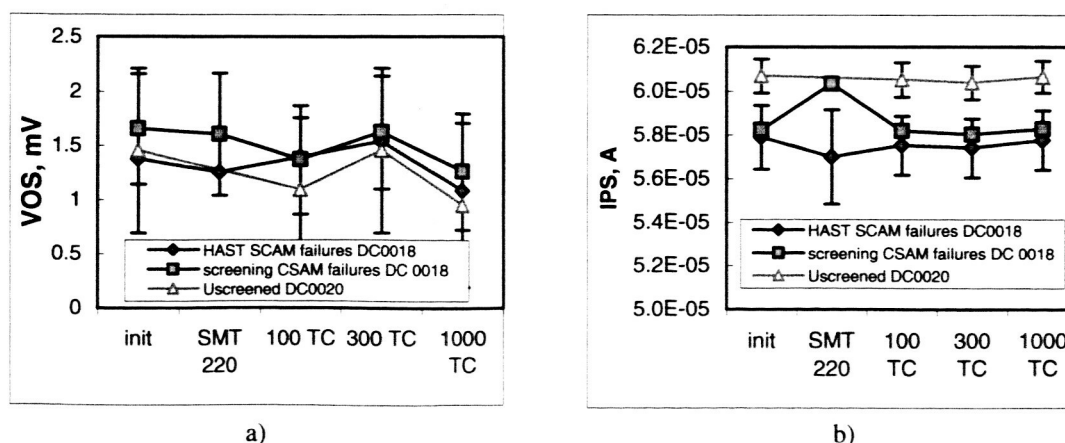a)   b)

Fig. 3. Effect of temperature cycling on electrical characteristics of the parts: a) offset voltage (VOS), b) power supply current (IPS).

The results indicate that gold-to-silver bonding, which typically is used as a secondary bond in PEMs, is strong enough and can provide reliable connection even in the presence of delaminations.

Case History II: BI-Induced Delaminations

Quad operational amplifiers encapsulated in 14-SO-style packages failed acoustic microscopy screening after BI testing, which was carried out at 85 °C for 590 hours, due to excessive delaminations at finger-tips in the secondary bond areas. Figure 4 shows X-ray views of the device, and Figure 5 shows typical acoustic microscopy images (C-SAM mode) of these devices before and after BI testing. Radiography and the following destructive physical analysis (DPA) showed that the device had two dice protected with a silicone die coating.
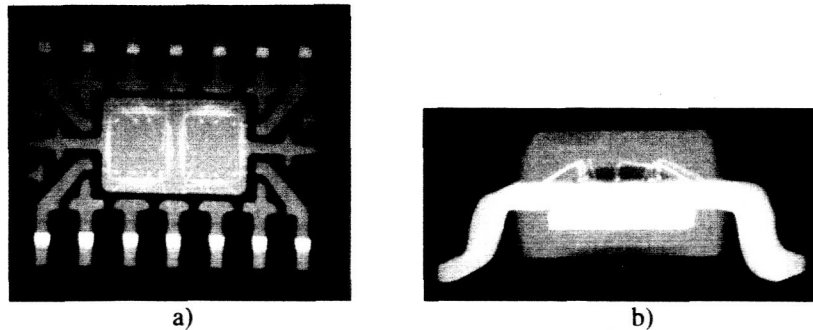

a)   b)

Fig. 4. Top (a) and side (b) X-ray views of the package showing a two-die device with a die coating.
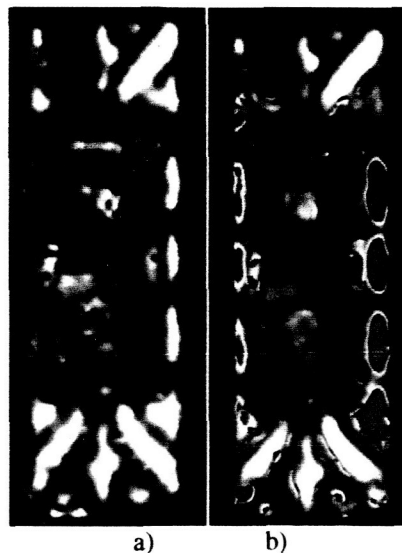

a)   b)

Fig. 5. Typical acoustic microscopy images before (a) and after (b) BI testing. Note that the finger-tip delaminations after BI testing were mostly formed on leads at the sides of the package and were not observed at the corner leads.

The BI testing, which had caused these failures, was performed at a relatively low temperature of 85 °C only. At these conditions, no significant mechanical stresses in the package are developed, and hence delaminations are unlikely to occur.

Thermo-mechanical characteristics of the molding compound used in these parts and deformations of the package are shown in Figure 6. The MC had Tg of 160 °C and CTE of 15.9 ppm/°C, which is typical for o-cresol novolack epoxy materials widely used for encapsulation of microcircuits. However, the effective CTE value calculated using deformations measured on the packages above the die locations were much larger, 22.8 ppm/°C. This is most likely due to the presence of the silicone coating, which has much larger CTE than the epoxy MC.
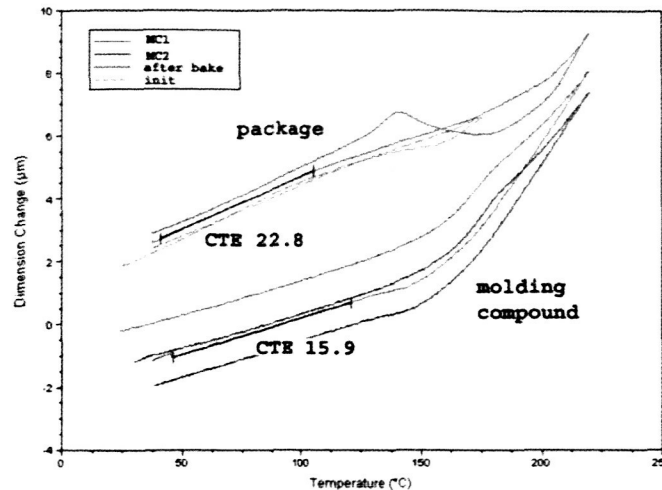
Fig. 6. Thermo-mechanical measurements of the molding compound and plastic packages used in the quad operational amplifiers.

The results allow for the following explanation of formation of the delaminations. At room temperature, the MC creates significant compressive stresses on the lead frame, and no delaminations are present. As the temperature increases, these stresses are decreasing while still remaining compressive at $T<Tg$. A long-term storage at 85 °C results in physical aging of MC and significant relaxation of the compressive stresses. The expansion of silicone coating increases the tensile stresses, resulting in development of forces repelling the MC from the LF at the leads, which are close to the coating. Creeping of MC caused by these forces creates delaminations with time of high-temperature aging. Possible redeposition of low molecular weight components, which typically are present in the silicone, onto the LF during curing of the coating reduces the adhesion of the MC and facilitates delaminations.

To analyze the significance of these delaminations for reliability of the parts, extensive testing has been performed. Three groups of parts, 22 samples each, after preconditioning per JESD22-A113-B were subjected to 200 temperature cycles between -55 °C and +125 °C; unbiased HAST at 130 °C, 85% RH for 96 hours; and life test for 1,000 hours at 125 °C. Electrical measurements at maximum, minimum, and room temperatures carried out after these tests did not reveal any failures, suggesting that delaminations at the finger-tips of the LF did not pose a reliability risk. Similar to the previous case, these data confirm the robustness of gold-to-silver wire bonding in PEMs, which concurs with the results of extensive reliability testing of plastic devices rejected due to delaminations in the secondary bond areas performed in [6].

Case History III: Wire Bond Failures

Multiple failures were observed during temperature cycling of sensors encapsulated in standard plastic 16-lead dual in-line packages (DIPs). Figure 7 shows an X-ray view of the part indicating a thick layer of die coating.
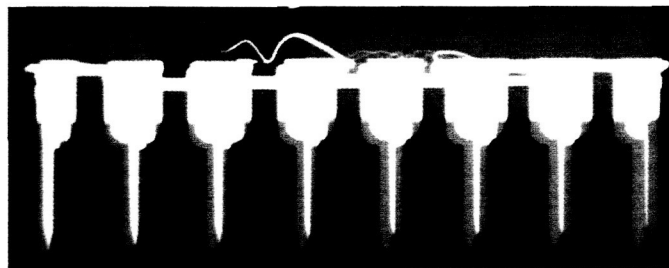

Fig. 7. Side X-ray view of the part.

Temperature cycling was performed on two groups of parts, 25 samples each, at the following two conditions: low-temperature range (-40 °C to +105 °C) and high-temperature range (-65 °C to +155 °C). Electrical characteristics of the parts were measured after 100, 200, 500, and 1,000 cumulative cycles in the first case; and

after 30, 100, 200, 300, 500, and 1,000 cumulative cycles in the second case. Results of these measurements are shown in Figure 8.
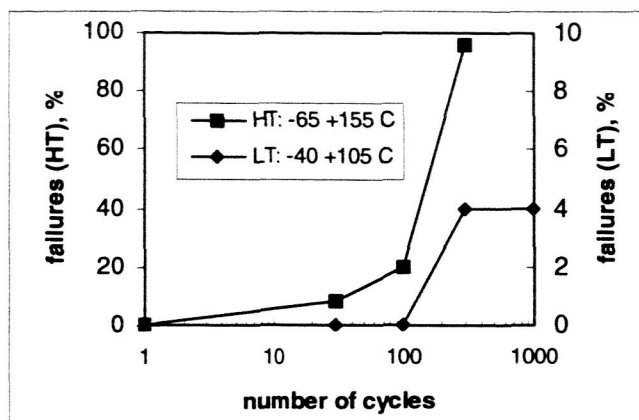

Fig. 8. Proportion of failures (%) versus number of temperature cycles.

Results of TMA for the MC and the package are shown in Figure 9. Similar to what was observed in Case II, the presence of silicone coating increased CTE in a glassy state of the polymer from 12.8 to 17.4 ppm/°C. However, substantial changes occurred in a rubbery state, where the effective CTE increased from 60.6 to 309 ppm/°C. The molding compound used had a relatively low Tg of approximately 134 °C, which explains the anomaly of large deformations at high temperatures and the high level of failures during the HT TC.
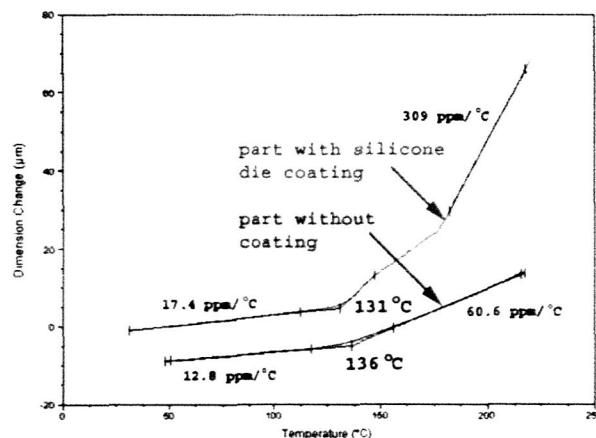

Fig. 9. Thermo-mechanical measurements of the molding compound and plastic packages used in sensors encapsulated in DIP-16 packages.

The TMA data indicate significant deformations of the silicone, which might result in fracture of the wire bonds. Internal examination of the failed parts (see Figure 10) confirmed that all observed failures were due to broken gold wires in the parts.
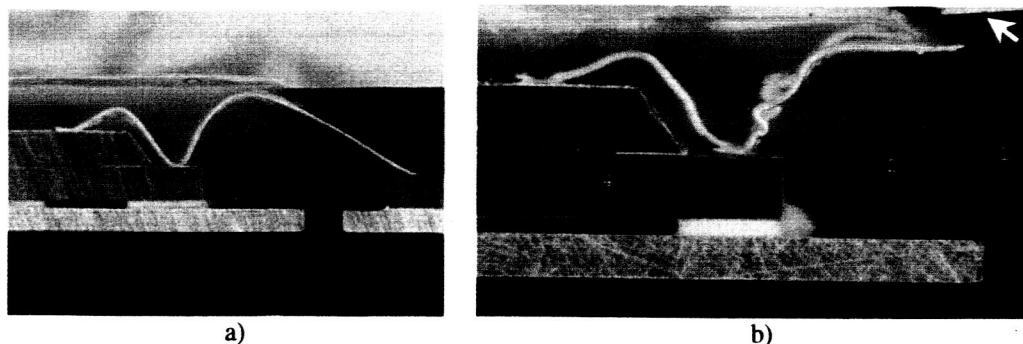
Fig. 10. Cross-section of a normal (a) and a failed (b) part showing a twisted and fractured wire: 1 – molding compound, 2 – silicone coating, 3 – lead frame, 4 – die. White arrow points at a broken wire.

Based on the observed data, the following failure mechanism can be suggested. As the temperature decreases, silicone shrinks, "clamps" the wire, and pulls it away from the MC. During temperature increase, the clamp is released, and the silicone expands and creeps along the wire towards the boundary with the MC. As the temperature decreases during the next cycle, the process repeats, thus twisting the wire and increasing its deformation. Eventually this process can lead to a fracture of the wire, as it is illustrated schematically in Figure 11.
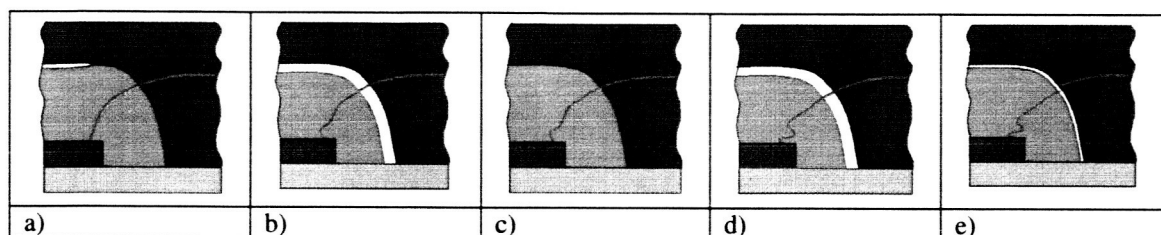

Fig. 11. The schematic of wire bond failures in PEMs with a relatively thick silicone die coating. Initial condition (a), at first cooling (b), at high temperature (c), repeat cooling (d), and a fracture after reaching the limit of gold wire deformation (e).

Note that to break a gold wire, a tensile deformation of ~4% to 6% has to be reached. Obviously, this deformation cannot be reached just by cooling a package with a relatively thin silicone die coating. However, with a relatively thick coating, multiple cycling might be capable of creating sufficient deformation to break the wire by the clamp-pull-and-creep mechanism.

Conclusion

1. Thermo-mechanical analysis of plastic packages has been shown to be an effective tool for quality evaluation and failure analysis of PEMs.
2. TMA measurements on PEMs with silicone die coatings have revealed excessive deformations, which explained the formation of delaminations at the lead finger-tips after burn-in testing. Similar delaminations were also observed after HAST, and were due to moisture-induced swelling and creep in the molding compound. Extensive reliability testing of the parts has shown that the gold-to-silver secondary wire bonds in PEMs are robust enough to withstand multiple temperature cycling even with finger-tip delaminations.
3. Deformations of DIP-16 plastic packages, due to the presence of a relatively thick layer of silicone coating, have been found responsible for failures of the parts due to fracture of gold bonding wires. A clamp-pull-and-creep mechanism has been suggested to explain multiple failures, which were observed during temperature cycle testing.

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